Self-Microlensing in Compact Binary Systems [1]

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ABSTRACT

The signature of the self-microlensing in compact binaries (white dwarfs, neutron stars and black holes) is a flare with the characteristic time of typically a few minutes. The probability of detecting these microlensing events can be as high as 1/50 for a flux sensitivity of $\Delta m = 0.01$ in magnitude. The discovery of the self-microlensing by binaries would furnish an additional way to find the masses of the lens and the companion and will be promising for the searches of black holes.

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The detection of the gravitational microlensing events and their relatively low detection rate in the Large Magellanic cloud (LMC) [1] have stimulated several studies on the possibility of attributing the LMC microlensing events to the stars and/or MAssive Compact Halo Objects (MACHOs) of the LMC itself [2,3]. Gould [4] referred to such a phenomenon as "self-lensing" and extended this research to the binary systems [5]. On the other hand, the binary stars are numerous and some of the microlensing events seen in the Galactic bulge are actually due to the microlensing by ordinary star binary systems [6]. Here we use the term "compact binary" to denote a binary system composed of two compact objects.

Gould [5] has estimated the optical depth τ to self-microlensing in various binary systems. It turns out that for a star binary system τ is too small ($\sim 10^{-11}$) to have any observational significance, while compact binaries composed of neutron stars or black holes may have a somewhat larger τ of up to 0.2% to generate observational features. In terms of these estimates, it appears to be very difficult and even hopeless to search for self-microlensing events in binaries considering the fact that the present-day discovered pulsar binaries are only a few tens.

We notice, however, that the optical depth to gravitational lensing only accounts for those events whose positions happen to appear within the Einstein rings of the lensing objects, which corresponds to a magnification of $\mu = 1.34$ or an apparent magnitude of $\Delta m = 0.32$. While the advanced detectors in today's astronomical observations can have a sensitivity of as high as $\Delta m \sim 10^{-3}$, the lensing probability p can be greatly increased if the small magnification events are taken into account. For instance, the above claimed optical depth of binary systems can be raised by a factor of ~ 10 if one includes the $\Delta m > 0.01$ events. This change is probably trivial for ordinary star binaries due to their extremely low optical depth, but would be of great significance for the compact binary systems. Actually, it will be promising to detect the self-lensing in a binary system composed of two compact objects like millisecond pulsars whose lensing probability is $p \sim 2\%$ for a sensitivity of $\Delta m = 0.01$. Motivated by this large lensing probability ($\sim 1/50$) for self-lensing in compact binary systems and the ~ 10 discovered pulsar/black hole binaries among the 706 pulsars observed so far, this paper presents an analysis of the microlensing features arising from the self-lensing in compact binaries and a tentative search for the self-lensing signatures from the existing catalogs.

We begin with a binary system composed of two compact objects with identical mass M and neglect their sizes and the possible occulation. Furthermore, we assume their rotating orbit to be a circle with separation of r. If we utilize D_d and D_s to denote the angular diameter distances from the observer to the lens and to the source, respectively, we have $D_d \approx D_s$. Either of the compact objects is able to gravitationally

magnify the brightness of its companion, depending on their positions and the orbital inclination i. The combined magnification of the lens-induced two images is

$$\mu = \mu_1 + \mu_2 = \frac{\ell^2 + 2a_E^2}{\ell\sqrt{\ell^2 + 4a_E^2}}, \tag{1}$$

where ℓ is the alignment parameter or the true position of the lensed companion

$$\ell = r\sqrt{1 - \sin^2 i \cos^2 \theta}, \tag{2}$$

a_E is the Einstein radius

$$a_E = \sqrt{\frac{4GM}{c^2} r \sin i \cos\theta} \tag{3}$$

and θ measures the position of the lensing object along its orbit with $\theta = 0$ at the closest point to the observer, i.e., μ takes the maximum at $\theta = 0$. The orbital motion of the source and lens would lead to the variation of the source brightness. Figure 1 shows a typical variation of source magnification within an orbital period (P) for a nearly edge-on compact binary composed of two objects with mass of $1M_\odot$ and separation of $R_\odot$. The lensing object temporarily magnifies its companion when the alignment parameter of the companion object reaches the minimum, which leads to a flare on the brightness of the companion. The characteristic time of this flare can be described by

$$\Delta T = \frac{P}{\pi}\sqrt{\frac{4GM}{c^2 r} u(\mu_{min}) - \left(\frac{\pi}{2} - i\right)^2}, \tag{4}$$

where μ_{min} is the minimum magnification corresponding to the flux sensitivity of the observation. It appears that for the example of Fig.1 and a period of $P = 1$ day, the time resolution should reach $\Delta T = 5(2)$ minutes to detect the $\Delta m > 0.01(0.1)$ event. Yet, it turns out to be feasible in observations, though it is much shorter than the timescale of the microlensing events in the LMC and in the Galactic bulge. Two flares in the combined light curves would occur within a period when both objects have electromagnetic radiation.

Unlike the microlensing events in the LMC and the galactic bulge where the distance and the transverse velocity of the lens are two unknown parameters, the microlensing in binaries is well constrained by their orbital parameters (i, P and r). This furnishes an additional way to estimate the mass of the lens using only the maximum magnification μ_{max}

$$M = \frac{c^2 r}{8G}(\sin^{-1} i - \sin i)\sqrt{\mu_{max}^2 - 1}(\mu_{max} + \sqrt{\mu_{max}^2 - 1}). \tag{5}$$

In particular, if the inclination i is close to $\pi/2$, we have

$$M = 18M_\odot\sqrt{\mu_{max}^2 - 1}(\mu_{max}^2 + \sqrt{\mu_{max}^2 - 1})\left(\frac{r}{R_\odot}\right)\left(\frac{90^\circ - i}{1^\circ}\right)^2. \tag{6}$$

Once the mass of the lens is determined, one can easily found the mass of the companion according to the Keplerian law. This method would be of great interest to the searches for black holes in binary systems.

We now examine our working hypothesis, i.e., the binaries are assumed to be pointlike. The Einstein radius from eq.(3) is estimated to be

$$a_E \sim 2.9 \times 10^{-3} \left(\frac{r}{R_\odot}\right)^{1/2} \left(\frac{M}{M_\odot}\right)^{1/2} R_\odot. \tag{7}$$

A detection sensitivity of $\Delta m = 0.01$ corresponds to a circle with radius of $3.6a_E$ around the lens, which is the size of the Earth ($R_\oplus$) for $r = R_\odot$ and $M = M_\odot$. Therefore, ordinary stars and the earth-mass planets cannot produce self-lensing effect due to their sizes being much larger than their Einstein radii. A white dwarf in a binary system can marginally act as a lens for its companion and a large separation of ~ 1 AU further reduces the occultation effect. On the other hand, the maximum magnification of a white dwarf with a size of $R_\oplus$ lensed by its compact companion with a mass of $M_\odot$ can reach $\mu_{max} = (1.2, 9.4)$ for the separation of $r = (R_\odot, 1 \text{ AU})$. It turns out that the white dwarf binaries can be considered as a good type of system for searches of self-lensing though a pointlike approximation might fail for a dwarf being the target source. As for a compact binary composed of two pulsars or black holes, the pointlike assumption should be a reasonable approximation since their sizes are much less than the Einstein radius given by Eq.(7).

The updated pulsar catalog contains 706 sources, among which 44 are binary systems including neutron star+ordinary star, neutron star+white dwarf, neutron star+planet, neutron star+black hole candidate and neutron star+neutron star. This number decreases if we exclude the systems having ordinary stars and/or planets. Furthermore, our study is limited to a few compact binaries since only 1/10 of the binaries have the orbital inclinations i observationally determined or constrained.

About 40% of the binaries are neutron star+white dwarf systems [7]. An interesting example is the millisecond binary pulsar PSR B1855+09 [8], which moves along a nearly circular orbit with a period of 12.3 days. The mass of the pulsar and of the companion white dwarf are $1.50M_\odot$ and $0.258M_\odot$, respectively. In particular, its orbital plane is nearly edge-on with $\sin i = 0.9992^{+0.0004}_{-0.0007}$. This large inclination makes it an attractive system for searches of the self-lensing signature. Unfortunately, the too large projected semimajor axis of $x = 9.23$ light seconds, which yields $r \approx 27R_\odot$ and the inclination $i = 87^\circ.7$, cannot result in any observational lensing features.

There are only four neutron star+neutron star systems and several neutron star+black hole candidate systems discovered to date. However, $\sim 10^5$ such systems are expected

to exist in our Galaxy [9]. About 2% of these binaries will show the signature of self-lensing and 0.2% of them would show strong self-lensing $\mu > 1.34$. Undoubtedly, this will provide a great number of samples for testing the general relativity and for discovering the black holes.

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Figure Caption

Fig.1. The microlensing induced brightness flare in a binary system composed of two compact objects with mass of $1M_\odot$ and separation of $R_\odot$. The orbital inclination is taken to be $89^\circ.9$. P denotes the period and Δm is the magnitude.